Race Yourselves: A Longitudinal Exploration of Self-Competition Between Past, Present, and Future Performances in a VR Exergame

Alexander Michael, Christof Lutteroth*
REal & Virtual Environments Augmentation Labs (REVEAL) University of Bath, UK

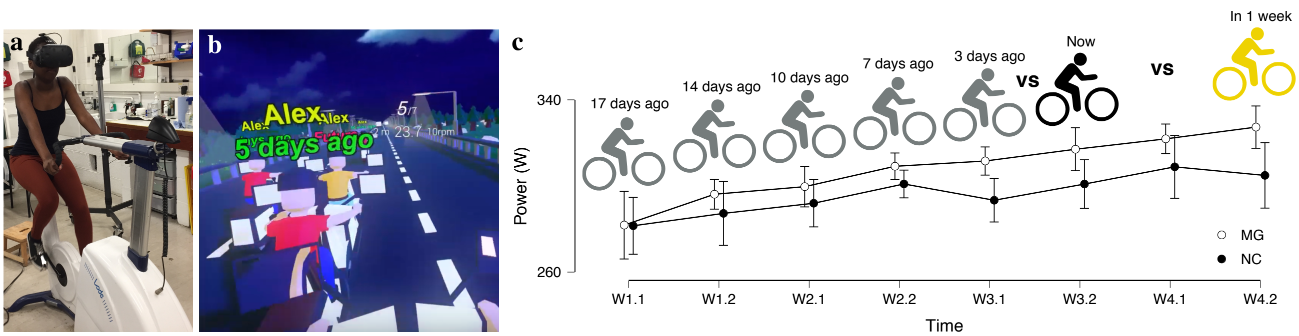

Figure 1. a) Players exercise on an exercycle while wearing a head-mounted display. b) Players race against their past and future selves represented as "ghost" avatars in high-intensity sprints. c) Players compete against all instances of their past performances and a projection of their future performance (MG), improving their performance (Power) more than a non-competitive exergame (NC). Each new session adapts the gameplay by adding a new ghost.

ABSTRACT
Participating in competitive races can be a thrilling experience for athletes, involving a rush of excitement and sensations of flow, achievement, and self-fulfilment. However, for non-athletes, the prospect of competition is often a scary one which affects intrinsic motivation negatively, especially for less fit, less competitive individuals. We propose a novel method making the positive racing experience accessible to non-athletes using a high-intensity cycling VR exergame: by recording and replaying all their previous gameplay sessions simultaneously, including a projected future performance, players can race against a crowd of "ghost" avatars representing their individual fitness journey. The experience stays relevant and exciting as every race adds a new competitor. A longitudinal study over four weeks and a cross-sectional study found that the new method improves physical performance, intrinsic motivation, and flow compared to a non-competitive exergame. Additionally, the longitudinal study provides insights into the longer-term effects of VR exergames.

*Correspondence: c.lutteroth@bath.ac.uk

CHI '20, April 25–30, 2020, Honolulu, HI, USA.

ACM ISBN 978-1-4503-6708-0/20/04 ...$15.00.
http://dx.doi.org/10.1145/3313831.3376256

Author Keywords
Self-competition; intrinsic motivation; performance; longitudinal; ghosts; exergame; virtual reality (VR)

CCS Concepts
•Applied computing → Computer games; Consumer health; •Human-centered computing → Virtual reality;

INTRODUCTION
Sedentary behaviour has detrimental consequences for health and well-being. Not only is a lack of physical activity strongly associated with obesity [140, 50] and sub-optimal mental health [118, 108], but it is also one of the leading causes of preventable death worldwide [86, 31, 107]. It is estimated that about 30% of adults and 80% of adolescents fail to meet public health guidelines for physical activity [66] all while dropout rates from exercise programs continue to hover around 50% [37, 4]. One of the strongest predictors of exercise adherence is intrinsic motivation [2, 122, 137], i.e. doing an activity for its inherent satisfaction and enjoyment. Alongside perceived lack of time, not enjoying exercise is commonly cited as the most important barrier to long-term exercise adherence [123, 136, 64]. Making exercise intrinsically motivating and time-efficient is, therefore, an important step towards tackling the global epidemic of sedentary behaviour.

Participating in racing sports can be a thrilling experience for many athletes. A rush of excitement, hope, stress, and anxiety mixed together with a heightened competitive drive to win can flood an athlete's mind in the lead up to an important race [113, 7, 30, 68, 82]. During a race, many athletes experience flow [73], a positive mental state where they are absorbed by their activity while deriving enjoyment from it [29]. The euphoric experience of winning a tough race is often accompanied by a boost in self-esteem, pride, and confidence [146, 14]. Racing can help satisfy the intrinsic need for achievement and self-fulfilment in a very visceral way [134], which can explain why many athletes find it extremely motivating [60].

As exciting as racing can be to athletes, its competitive nature is not appealing to everyone. There is a wide literature showing that competing against others can have detrimental effects on intrinsic motivation, especially for less fit, less competitive individuals [32, 130, 141, 8, 115, 52, 33]. In particular, the stigma of losing and the low self-esteem one suffers after failing to do well in competitive activities can have very damaging effects on intrinsic motivation and perceived competence [87, 49]. Losing to others can also be a source of humiliation and embarrassment [93], emotions that many people go to great lengths to avoid [78]. Cognitive evaluation theory [120] suggests that low perceived competence in an activity translates into diminished intrinsic motivation [34], i.e. it is difficult for someone to enjoy an activity they do not feel they are good at. Losing badly can shatter perceived competence and is a risk unfit people face when it comes to competitive sports. Given these tough psychological obstacles, can we make the positive racing experience that athletes find so enticing accessible to less fit and less competitive individuals?

Exergaming, which makes exercise more intrinsically motivating through gamification [103], yields a potential solution: self-competition. Self-competition is a common feature of many racing video games [26] where players race against an opponent that is a replay or "ghost" of one of their past performances. Promising evidence suggests that, for a general population, self-competitive exergaming is superior to racing against others in terms of elicited performance and intrinsic motivation [10, 125, 44]. These observations are in line with flow theory, which highlights the importance of competing against opponents with similar abilities to stimulate engagement and enjoyment in competitive settings [73, 95, 28, 75]. Given that the best match against someone's own skills and abilities is themselves, self-competition exergaming offers a uniquely fair approach to the racing experience that gives less fit and less competitive individuals a realistic chance of winning and a better opportunity to experience the positive side of racing.

The problem with existing forms of self-competitive exergaming is that players only compete against a single past performance [10, 44, 125], which limits the richness of the racing experience. Unlike one-on-one competition, being surrounded by and competing against a spectrum of differently skilled competitors creates a shared experience that is a key ingredient of many exciting races both in video games and in real life [63, 147, 67]. To bridge the gap between self-competition and such a rich racing experience, we propose a novel approach in which players race against their own *performance history* as well as a model of their future performance using multiple ghost avatars (Figure 1c), creating a new form of competition that has not been previously explored.

We decided to implement our "multi-ghost" approach in a high-intensity cycling exergame using VR to evoke the same visceral sensations felt during a real racing event [116, 67], given the effectiveness of VR at increasing intrinsic motivation, flow, embodiment, and immersion [44, 127, 98, 148, 71]. With the rise of all-in-one head-mounted displays (HMDs), VR could be a more practical solution than using large monitors [94] in terms of facilitating usage of the exergame in existing gym setups given its small spatial footprint and availability.

Having players race against their past and future selves in an immersive virtual environment offers the following potential advantages:

Fairness: Because competitors are all generated from the player's own performances, competition becomes inherently fair and personalised to each player's fitness ability. This helps to strike the right balance between skill and challenge, which facilitates flow [28, 110] and intrinsic motivation [77, 69].

Feedforward is a psychological training technique used to achieve rapid performance improvement by establishing an image of an ideal future self that the present self can learn from [40]. Allowing players to compete against a "future ghost", which is an enhanced self-model of their best performance to date, can motivate them to exercise at a higher intensity without negatively impacting their intrinsic motivation [10]. This would help them achieve their fitness goals more quickly.

Self-Efficacy, the confidence in one's ability to carry out a task under challenging circumstances [9], is an important predictor of exercise adherence [35, 90]. Self-competitive exergaming can avoid the common detrimental effects of conventional competition on self-efficacy [10, 130, 115] and beating your own ghosts could cultivate perceived competence, an important contributor to self-efficacy [1].

Adaptability: The latest ghosts reflect the player's latest performances, so as players improve, so do their competitors. This adaptive approach to increasing competitive pressure encourages players to continually improve their performance, but in a way that always maintains a balance between the challenge and the player's current skill [73].

Replayability: After each game session, a new ghost is generated and added to the set of competitors. Competing against an extra ghost every time the game is played again ensures that the competitive dynamics are never the same. This helps increase the replay value of the exergame [80] and makes it more likely to sustain interest over the longer term, hence addressing a common limitation of existing exergames [88].

While promising, the longer-term physiological and psychological effects of multi-ghost competition have yet to be explored. The few related exergaming studies on self-competition have all been cross-sectional and only involved competing against a single ghost [10, 44, 125]. In fact, researchers agree that more longitudinal studies are needed to clarify the long-term effects of exergames in general: systematic reviews of exergames highlight that most of the studies have been cross-sectional, while the longitudinal studies that do exist tend to just evaluate exergames for physical rehabilitation [129, 79, 11] or low-to-moderate-intensity exercise [81, 85, 133]. In terms of physiological outcomes, the longitudinal studies typically measure outcome variables such as energy expenditure, heart rate, and weight loss – yet neglect to measure performance improvement [133, 135, 76, 55], an important indicator of an exergame's ability to increase fitness over time. To fill these important gaps in the research literature, we present a longitudinal and a cross-sectional study, together with a thematic analysis, evaluating our high-intensity VR exergame. To the best of our knowledge, we are the first to explore the longitudinal effects of high-intensity exergames and the first to explore self-competition between past, present, and future player performances. In doing so, this paper aims to answer the following research questions:

RQ1 How effective is multi-ghost competition in improving exercise performance over time?
RQ2 How does multi-ghost competition affect psychological predictors of exercise adherence over time?
RQ3 How does multi-ghost competition compare to non-competitive gameplay?

In summary, we make the following contributions:

1. A novel form of self-competition in exergames that enables competition between players' past, present, and future performances using multiple ghosts.
2. Empirical evidence supporting that multi-ghost competition can be an effective method for improving player performance over time whilst improving psychological predictors of exercise adherence.
3. Empirical evidence supporting that multi-ghost competition can make the positive aspects of the racing experience accessible to non-athletes.

RELATED WORK

Evidence suggests that self-competition exergames can make less competitive individuals more receptive to competition [10, 125, 44]. This may be because self-competition can help strike the ideal balance between skill and challenge that is key to achieving flow [97] and for making the experience intrinsically motivating [77, 69]. Indeed, compared to non-competitive gameplay and competition against others, self-competition exergaming has been shown to increase performance while not negatively affecting intrinsic motivation [10, 44] – results that highlight the importance of nuanced competition framing around the self. This contrasts with findings from Song et al. detailing the detrimental effects competing against others in exergames can have on self-efficacy and intrinsic motivation for non-competitive individuals [130]. These observations can be explained in terms of the player's locus of control, i.e the degree to which players believe they have control over event outcomes [119]. Those with an internal locus of control tend to credit or blame themselves for the results of event outcomes and thus tend to find greater satisfaction in their achievements [38]. In contrast, those with an external locus of control tend to credit or blame external factors as determinants of event outcomes [106]. Competing against others could be associated with an external locus of control since competitor skill is something that is outside of the player's control. On the other hand, the receptive response to self-competition by less competitive individuals might be caused by a shift towards an internal locus of control: a stronger belief that they can actually win given it is not an unreasonable expectation to match or do better than an earlier performance. An internal locus of control may also help to mitigate the shame of losing [92], which can otherwise have a strong negative impact on self-perceptions and self-esteem [49], especially for people stigmatised for their perceived lack of fitness [112].

Self-competition is a staple feature of many racing video games and is usually implemented by having players compete against a self-model "ghost", a recording of one's past performance played back as a competitor [26]. Unlike competing against other players or an AI opponent, ghosts perfectly mirror a given player's performance level, which helps to balance the competitive challenge to suit their current abilities. The concept of competing against a ghost has been around as early as 1992 in the first Super Mario Kart game [105] and there have even been some games such as Super Meat Boy and Trackmania where players can see multiple past ghosts during gameplay. However, it is only more recently that the idea of self-competition with ghosts has been explored in the domain of exercise. For example, Nike built an interactive running track surrounded by LED displays where runners compete against a projected digital avatar representing their best lap time [132]. Popular mobile fitness apps for running and cycling such as Endomondo [43] and Ghostracer [138] have ghost systems that give real-time audio feedback on how the user's current performance compares to a previous session. Despite some evidence suggesting that multiple ghosts (MG) can be distracting and counterproductive for non-exertion games [42], it is unclear whether or not such findings hold when adapting MG as a form of self-competition in exergames.

Related to the idea of self-modelling is feedforward, a psychological training technique [40, 41, 39]. While feedback uses past information to inform behaviour change, feedforward tries to establish an image of a future ideal self that the present can learn from. In order to achieve feedforward effects, a self-model must be constructed that 1) shows a future ideal self carrying out the desired behaviour and 2) the individual identifies with [40]. Feedforward has been used in the form of video self-modelling where users watch an edited video of themselves performing optimally, with success in sports, education, and therapy [149, 117, 20, 131, 27]. Feedforward has also been used in an interactive format for VR exergaming by augmenting the perceived performance of the player [72] and – similar to our proposed method – by allowing players to race against a ghost of their previous performance under increased exercycle resistance [10, 44]. Barathi et al. [10] found that interactive feedforward can be more effective than self-competition at improving performance while maintaining intrinsic motivation and confirmed the importance of identifying with the self-model. Players who were not told that a ghost represented their own performance had lower intrinsic motivation, flow, and power output. This suggests that self-competition can avert the potential negative effects of competing against others, at least in the short term. The longer-term effects of self-competition and feedforward on performance and motivation have not been studied before.

EXERGAME DESIGN

Our exergame is a high-intensity VR racing game in which players compete against multiple ghosts representing their history of past performances as well as a projected future performance (Figure 1c). Players ride an exercycle ergometer while wearing an HTC Vive HMD (Figure 1a). Similar to the exergame by Barathi et al. [10], the player cycles along a straight road containing three lanes that are populated by their ghosts and slow-moving trucks. The player's in-game speed is proportional to their cycling speed. By tilting their head slightly left or right, the player can move laterally towards the left or right side of the road.

The exergame implements a 5-minute High-Intensity Interval Training (HIIT) protocol, alternating between periods of low-intensity cycling and high-intensity sprints. During the low-intensity phase, players cycle at a relaxed pace while dodging the trucks on the road; during sprints, players race against their aforementioned ghosts (Figure 1b). At the beginning of each sprint, the ghosts and the player are placed at the same position to ensure a fair start. A head-up display shows the player's current cadence, their distance behind or ahead of their projected future ghost, their current ranking position within the crowd of ghosts, and a countdown timer indicating when the current exercise phase ends.

Each gameplay session records the player's performance and adds a new ghost to the game. To achieve a feedforward effect, the ghost representing the projected future performance is based on the player's best recorded performance to date sped up by 5%. This represents a performance improvement that is realistically achievable for most people in the short-to-medium-term [74, 21, 62, 84, 144, 70, 124, 99, 83]. To facilitate identification, the player's name floats atop each ghost together with a label describing when the ghost was recorded to make it easier to gauge training progress (Figure 1b). Additionally, all ghosts are based on the same visual model as the player's avatar: past ghosts wear the same red shirt and blue pants, while the future ghost wears a yellow shirt and white pants to make it a clearly distinguishable target. All ghosts recorded to date are played back in each session.

A HIIT exercise protocol was chosen because of its time efficiency [59, 84] and effectiveness in improving fitness-related measures [58, 145, 114]. We chose a 5-minute protocol [10]: 60 sec warm-up, 30 sec sprint, 90 sec recovery, 30 sec sprint, and 90 sec cool-down. Limiting exercise to 5 minutes likely helped prevent the onset of VR sickness [96] as well as mitigate any potential discomfort from exercising with an HMD. During the low-intensity phases, the bike resistance was set to a low value of 12 Nm. During the two high-intensity sprints, the bike resistance was set based on the participant's mass to 0.4 Nm kg^{-1}; this was adjusted in a familiarisation phase to enable each participant to exert themselves while avoiding uncontrolled leg movements.

LONGITUDINAL STUDY

We conducted a between-participants longitudinal study investigating the long-term effects of multi-ghost competition on performance (RQ1) and psychological predictors of exercise adherence (RQ2). Similar to other longitudinal studies of HIIT training [62, 59, 84], participants played the exergame twice a week over four weeks with gameplay sessions separated by at least one day of rest: either under the Multi-Ghost (MG) condition or the No Competition (NC) control condition. NC did not feature any ghosts but was otherwise identical to MG; it represents a fairly typical, non-competitive cycling-based VR exergaming experience [10, 125, 126, 127, 16] consistent with the way HIIT would typically be practised in a gym [102, 101].

The gameplay experience of NC remained identical across all eight sessions. Session 1 of MG was identical to NC as a first baseline performance was recorded. In session 2, MG participants competed against one past and one future ghost based on their baseline, with each subsequent session adding another past ghost. In session 8, MG participants competed against seven past ghosts and one future ghost.

Outcome Variables

Performance was measured using a Lode Excalibur Sport exercycle by recording the average power output (Power) in Watts during the two sprints. To measure performance improvement, we consider the difference in power output (ΔPower) from the participant's baseline performance in session 1. *Exertion* was measured based on a participant's average (HR Avg%) and peak (HR Peak%) heart rates using a Polar H7 chest strap heart rate monitor. HR was expressed as a percentage of a participant's maximum, estimated as 220 minus age based on ACSM guidelines [102]. Additionally, participants gave a verbal rating of perceived exertion (RPE) on a scale of 1 (lowest) to 10 (highest) immediately after the end of each sprint using the Borg CR-10 scale [17]. *Intrinsic motivation* was measured using the Intrinsic Motivation Inventory (IMI) [120], which has been widely used for physical activity [91, 24], from 1 (lowest) to 7 (highest), including the main Interest/Enjoyment subscale as well as auxiliary subscales for Effort/Importance, Pressure/Tension, and Perceived Competence. *Flow* was measured using the Flow Scale Questionnaire (FSQ) [89] from the Positive Psychology Lab, which has been validated with exergames, from 1 (lowest) to 5 (highest), including the two subscales Balance of Challenges and Skills, and Absorption in the Task. *Qualitative feedback* was elicited at the end of each session in short interviews starting with the question "How did it go today?". In the final session, a more comprehensive questionnaire was given to capture the participant's feelings about their overall experience (likes/dislikes and overall comments).

Procedure

Participants were first screened for health concerns using the Physical Activity Readiness Questionnaire (PAR-Q) [139]. Participants then completed a demographics questionnaire, the Sports Orientation Questionnaire (SOQ) as a measure of sports-specific motivation (competitiveness, goal orientation, and win orientation) [61], and finally the International Physical Activity Questionnaire (IPAQ) to estimate their general level of physical activity [65]. To mitigate any learning effects on cycling, participants took part in a familiarisation session where they experienced the flow of the exergame. Participants were randomly assigned to either MG or NC and played the respective exergame in the following eight sessions over four weeks. At the end of each session, participants completed the IMI and FSQ questionnaires after giving qualitative comments on their experience.

Hypotheses

We posed the following a-priori hypotheses:

H1 Multi-ghost competition (MG) is more effective at improving performance than no competition (NC) (RQ1).
H2 Participants exert themselves more in multi-ghost competition (MG) compared to no competition (NC) (RQ1).
H3 Multi-ghost competition (MG) is more intrinsically motivating than no competition (NC) (RQ2).
H4 Multi-ghost competition (MG) elicits stronger feelings of perceived competence than no competition (NC) (RQ2).

Participants

Originally, 24 participants were recruited using posters and through word-of-mouth. One participant dropped out due to motion sickness making for a total of 23 participants: 12 in group MG (6 male, 6 female; age 19-22, mean 20) and 11 in group NC (8 male, 3 female; age 19-24, mean 21). All participants were students at the University of Bath. Based on body mass index guidelines [54], of the MG participants, one participant was underweight, eight had normal weight, and three were overweight. Of the NC participants, three participants were underweight, five had normal weight, and three were overweight.

Results

A summary of the results is shown in Table 1. The two conditions were compared using multilevel linear regression models in R through the nlme package [15] because of their power and flexibility when analysing longitudinal data [25, 111]. The condition (MG vs NC) and the sessions (1 to 7) were set up as fixed effects. The regression analysis excludes the first session because it was merely used to establish a baseline and was identical for both MG and NC. Session was set up as time covariate and participant as a grouping factor, so that session was treated as a within-participant effect. Positive regression coefficients B for the condition indicate the estimated value by which an outcome variable is greater for the MG intervention compared to control (MG > NC) and vice versa for negative coefficients (NC > MG). We use one-tailed tests for our hypotheses and two-tailed tests otherwise. We report the 95% confidence intervals CI of coefficients, test for significance with $\alpha = .05$, and show 95% confidence intervals of the mean in all graphs. We denote each exergaming session as W*week.session*, e.g. W4.2 is the second session of week 4.

Power. An independent-samples t-test showed that there were no significant differences in the baselines for ΔPower between MG and NC ($t(21) = 0.01, p = .990$); the two groups performed very similarly. In the following sessions, participants in MG had significantly higher ΔPower compared to those in NC (Figure 1c, $B = 15.38W, CI = [5.25W, 25.51W], t(21) = 3.00, p = .003^{**}$), therefore we accept H1. Both groups significantly increased ΔPower over the sessions ($B = 4.41W, CI = [2.57W, 6.25W], t(22) = 4.72, p < .001^{***}$).

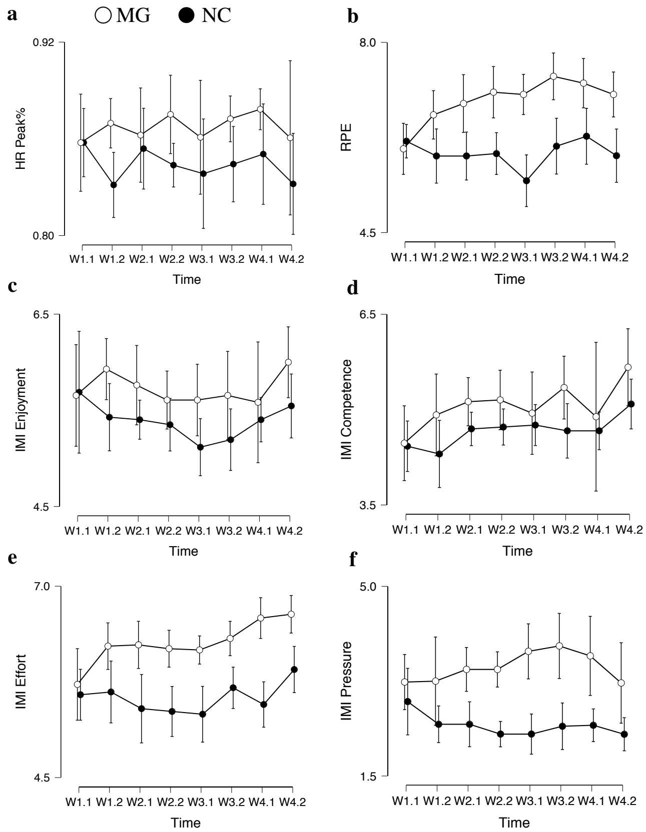

Figure 2. Longitudinal results in MG vs. NC for a) HR Peak%, b) RPE, c) IMI Interest/Enjoyment, d) IMI Perceived Competence, e) IMI Effort/Importance, and f) IMI Pressure/Tension.

Exertion. Independent-samples t-tests showed that there were no significant differences in the baselines for HR Avg%, HR Peak%, and RPE between MG and NC ($t(21) < 0.59, p > .565$). In the following sessions, participants in MG had significantly higher HR Avg% ($B = 3.19\%, CI = [0.36\%, 6.03\%], t(21) = 2.22, p = .019^{*}$) and significantly higher HR Peak% (Figure 2a, $B = 2.95\%, CI = [-0.26\%, 6.16\%], t(21) = 1.81, p = .042^{*}$) and significantly higher RPE (Figure 2b, $B = 1.12, CI = [0.06, 2.17], t(21) = 2.09, p = .024^{*}$) compared to those in NC. This indicates that MG participants exerted themselves more than NC participants, therefore we accept H2.

Intrinsic Motivation. Independent-samples t-tests showed that there were no significant differences in the baselines for any of the IMI subscales between MG and NC ($t(21) < 0.94, p > .360$); the two groups were similarly intrinsically motivated to start with. In the following sessions, participants in MG had significantly higher IMI Interest/Enjoyment scores compared to those in NC (Figure 2c, $B = 0.55, CI = [0.10, 1.00], t(21) = 2.39, p = .013^{*}$), therefore we accept H3. Participants in MG also had significantly higher IMI Perceived Competence scores compared to those in NC (Figure 2d, $B = 0.73, CI = [-0.08, 1.54], t(21) = 1.77, p = .046^{*}$), therefore we accept H4. Furthermore, MG participants had higher IMI Effort/Importance scores (Figure 2e, $B = 0.84, CI = [0.51, 1.17], t(21) = 5.03, p < .001^{***}$), indicating

Table 1. Summary of demographics and results at the beginning, middle, and end of the longitudinal study for each group (mean ± std. dev.).

Game Condition	n	Demographics	Variable	Session		
				W1.1	W2.2	W4.2
Multi-Ghost (MG)	12	m=6, f=6 age=20.00±1.35 BMI=22.68±3.51 IPAQ=1767±1098 MET SOQ Comp.=3.15±0.82 SOQ Win=2.99±0.60 SOQ Goal=3.89±0.68	Power	281.82±90.86	309.13±103.08	327.32±95.23
			ΔPower		27.31±30.04	**45.5±32.23
			HR Avg%	78.99±6.15	80.21±6.43	*79.27±7.65
			HR Peak%	85.76±6.30	87.51±6.31	*86.06±8.06
			RPE	6.04±1.47	7.08±0.82	*7.04±1.20
			IMI Enjoyment	5.65±0.78	5.61±0.71	*6.00±0.69
			IMI Effort	5.72±0.88	6.18±0.62	***6.63±0.46
			IMI Pressure	3.23±0.91	3.47±0.73	**3.22±1.36
			IMI Competence	4.47±1.06	5.15±1.21	*5.67±1.06
			FSQ Balance	3.98±0.76	3.85±0.67	3.96±0.77
			FSQ Absorption	3.67±0.60	3.92±0.63	4.13±0.59
No Competition (NC)	11	m=8, f=3 age=20.73±1.49 BMI=21.85±4.23 IPAQ=2903±1738 MET SOQ Comp.=3.43±0.83 SOQ Win=3.12±0.77 SOQ Goal=4.05±0.49	Power	281.51±116.35	300.92±112.99	304.90±115.02
			ΔPower		19.41±21.39	23.39±33.57
			HR Avg%	77.52±5.88	76.36±4.37	77.19±4.50
			HR Peak%	85.77±4.46	84.37±4.95	83.21±5.80
			RPE	6.18±1.55	5.95±1.63	5.92±1.41
			IMI Enjoyment	5.69±1.05	5.35±1.23	5.55±0.90
			IMI Effort	5.58±1.10	5.36±1.23	5.91±0.90
			IMI Pressure	2.87±0.93	2.27±0.97	2.27±1.20
			IMI Competence	4.42±1.21	4.73±1.35	5.09±1.40
			FSQ Balance	4.13±0.52	3.88±0.61	4.01±0.73
			FSQ Absorption	4.03±0.38	3.88±0.71	3.99±0.65

* significant at $p < .05$; ** significant at $p < .01$; *** significant at $p < .001$.

that MG motivated participants to put more effort into the game than NC, and higher IMI Pressure/Tension scores (Figure 2f, $B = 0.98, CI = [0.42, 1.53], t(21) = 3.46, p = .002^{**}$), indicating that MG created greater feelings of pressure and tension than NC.

Flow. The differences in FSQ Balance scores ($B = 0.08, CI = [-0.33, 0.48], t(21) = 0.39, p = .702$) and FSQ Absorption scores ($B = 0.08, CI = [-0.33, 0.48], t(21) = 0.39, p = .702$) between MG and NC were not significant. Both groups significantly increased their FSQ Absorption scores over the sessions ($B = 0.03, CI = [0.003, 0.05], t(22) = 2.25, p = .035^{*}$), indicating that participants got slightly more absorbed into the exergames over the course of the study.

Effects of Sport-Specific Motivation. To understand the longitudinal effects of a participant's sport-specific motivation, we extended our multilevel linear regression models with additional fixed-effects factors for SOQ Competitiveness, Win Orientation, and Goal Orientation. To account for the additional tests, we adjusted the p-values of the SOQ subscale coefficients with Holm correction. Independent-samples t-tests showed that there were no significant differences in the baselines of these SOQ subscales between MG and NC ($t(21) < 0.79, p > .437$); both groups had similar sport-specific motivation.

SOQ Goal Orientation contributed significantly to higher power output ΔPower ($B = 16.46W, CI = [6.61W, 24.31W], t(21) = 4.143, p < .001^{***}$), but SOQ Competitiveness ($B = -5.48W, CI = [-11.95W, 0.98W], t(21) = -1.67, p = .218$) and SOQ Win Orientation ($B = -1.03W, CI = [-8.81W, 6.74W], t(21) = -0.26, p = .800$) did not contribute significantly. Accounting for sport-specific motivation through the SOQ brought out the positive effect of MG vs NC ($B = 22.64W, CI = [13.60W, 31.68W], t(21) = 4.95, p < .001^{***}$) and Session ($B = 4.04W, CI = [6.61W, 24.31W], t(22) = 10.88, p < .001^{***}$) on ΔPower more clearly. All this indicates that participants who are goal-oriented, i.e. who place importance on their personal performance goals as opposed to beating other people, derive particular benefit with regards to improving their physical performance.

SOQ Win Orientation contributed significantly to lower IMI Interest/Enjoyment scores ($B = -0.70, CI = [-1.10, -0.30], t(21) = -3.46, p = .006^{**}$), but SOQ Competitiveness ($B = 0.13, CI = [-0.20, 0.47], t(21) = 0.80, p = .430$) and SOQ Goal Orientation ($B = 0.32, CI = [-0.08, 0.72], t(21) = 1.59, p = .254$) did not contribute significantly, while the effect of Condition remained significant ($B = 0.43, CI = [-0.02, 0.88], t(21) = 1.88, p = .037^{*}$). SOQ Goal Orientation contributed significantly to lower IMI Pressure/Tension scores ($B = -0.69, CI = [-1.05, -0.33], t(21) = -3.76, p = .004^{**}$), but SOQ Competitiveness ($B = -0.18, CI = [-0.45, 0.09], t(21) = -1.35, p = .369$) and SOQ Win Orientation ($B = 0.23, CI = [-0.10, 0.55], t(21) = 1.37, p = .369$) did not contribute significantly, while the effect of Condition remained significant ($B = 0.93, CI = [-0.02, 0.88], t(21) = 4.65, p < .001^{***}$). All this indicates that participants who were win-oriented, i.e.

Table 2. Results of the cross-sectional study (mean ± std. dev.).

Variable	Multi-Ghost (MG)	No Competition (NC)
Power	***332.07±111.08	300.62±6.11
HR Avg%	81.26±6.68	78.62±5.55
HR Peak%	87.91±6.60	85.04±5.09
RPE	*7.13±1.49	6.48±1.37
IMI Enjoyment	***5.98±0.88	5.22±1.11
IMI Effort	**6.39±0.97	5.50±1.33
IMI Pressure	*3.17±1.28	2.59±1.28
IMI Competence	**5.68±1.11	5.08±1.22
FSQ Balance	4.13±0.67	3.99±0.77
FSQ Absorption	***4.25±0.62	3.75±0.75
ESE Self-Efficacy	*6.62±2.26	6.37±2.30
Future Usage	*6.05±1.09	5.30±1.40

* significant at $p < .05$; ** significant at $p < .01$; *** significant at $p < .001$.

focused on beating others, enjoyed the exergaming experience less than those who were not and that participants who focused on their personal performance goals, as opposed to beating others, experienced less pressure and tension.

CROSS-SECTIONAL STUDY

To further address RQ3, all 23 participants took part in a cross-sectional study with a within-participants design after completing the longitudinal study. It was conducted in an additional session where they played the exergame under conditions MG and NC in a counterbalanced order. In the longitudinal study, all performances of group NC were recorded just as they were for group MG; so the NC participants were now able to experience the exergame with their past and future ghosts in the same manner as the MG participants.

All participants were thoroughly briefed and familiarised with both conditions. To mitigate fatigue, participants rested for at least 10 minutes between conditions until they felt ready to play the game again. After each condition, participants completed the same questionnaires as in the longitudinal study. Additionally, participants completed the "Internal Feelings" subscale of the revised Exercise Self-Efficacy Scale (ESE) [128], which measures self-efficacy based on feelings as an important long-term predictor of exercise [56]. Participants also rated how likely they were to use the exergame of the respective condition in the future (Future Usage, 1=very unlikely, 7=very likely). At the end of the session, participants were interviewed about their preference. We hypothesised that all outcome measures would be higher in MG than in NC.

Results

A summary of the results is shown in Table 2. According to a power analysis, the one-tailed paired t-tests used were able to detect medium-sized effects (Cohen's $d = 0.54$) between the conditions at $\alpha = 0.05$ with a power of 0.80.

Power. A one-tailed paired-samples t-test for Power showed that MG led to significantly higher power output compared to NC ($t(22) = 4.29, p < .001^{***}$), with a "large" effect size (Cohen's $d = .89$). One-tailed paired-samples t-tests for Power in sprint 1 ($t(22) = 4.00, p < .001^{***}$) and sprint 2 ($t(22) = 3.98, p < .001^{***}$) showed that in both sprints, MG led to significantly higher power output compared to NC, with "large" effect sizes (both Cohen's $d = 0.83$).

Exertion. One-tailed paired-samples t-tests showed that the differences in HR Avg% ($t(22) = 1.53, p = .070$) and HR Peak% ($t(22) = 1.66, p = .055$) between MG and NC were not significant. A one-tailed paired-samples t-test showed that RPE in MG was significantly higher ($t(22) = 2.31, p = .015^{*}$) than in NC, with a "medium" effect size (Cohen's $d = 0.48$).

Intrinsic Motivation. One-tailed paired-samples t-tests comparing MG and NC showed that MG led to significantly higher IMI Interest/Enjoyment scores ($t(22) = 3.86, p < .001^{***}$), with a "large" effect size (Cohen's $d = .81$), significantly higher IMI Effort/Importance scores ($t(22) = 3.15, p = .002^{**}$), with a "medium" effect size (Cohen's $d = .66$), significantly higher IMI Pressure/Tension scores ($t(22) = 1.83, p = .040^{*}$), with a "small" effect size (Cohen's $d = 0.38$), and significantly higher IMI Perceived Competence scores ($t(22) = 3.11, p = .003^{**}$), with a "medium" effect size (Cohen's $d = .65$).

Flow. A one-tailed paired-samples t-test for FSQ Balance showed that there was no significant difference between MG and NC ($t(22) = 0.98, p = .168$). A one-tailed paired-samples t-test for FSQ Absorption showed that MG led to significantly higher absorption ($t(22) = 4.76, p < .001^{***}$) than NC, with a "large" effect size (Cohen's $d = .99$).

Exercise Self-Efficacy, Future Usage, and Preference. One-tailed paired-samples t-tests comparing MG and NC showed that MG led to significantly higher exercise self-efficacy ($t(22) = 1.97, p = .031^{*}$), with a "small" effect size (Cohen's $d = .41$), and that participants were significantly more likely to continue using the MG exergame in the future ($t(22) = 2.51, p = .010^{*}$), with a "medium" effect size (Cohen's $d = .54$). All participants unanimously preferred MG over NC.

THEMATIC ANALYSIS

To better understand our participants' experience with the exergame, we analysed their qualitative feedback using inductive thematic analysis from a critical-realist perspective [19]. To begin, all qualitative feedback was collated, read, and re-read to get familiar with the contents of the data. This was followed by systematically coding any interesting remarks that seemed relevant to our research questions. Together with their attached data, similar codes were clustered together to identify a central organising concept that could give rise to a potential theme. As the themes evolved, they were recursively checked against the data set to ensure they continued to tell a coherent story of the data. Finally, an analysis of each theme was developed and weaved together with selected extracts to form an analytic narrative of our participants' experience. The extracts are presented as is without any spelling or grammatical corrections.

Theme 1: I am getting better and better

A common pattern observed throughout the longitudinal data was the sense that participants across both MG and NC felt that they were improving their performance as the study went on (*"[Today went] really well! I think my performance has definitely improved since my first session"*, *"better than last time"*). Participants in MG were able to make concrete appraisals of their performance because beating their ghosts gave clear feedback they had improved (*"I like to compare myself so i can gauge my performance"*). By having multiple ghosts, they were able to make more nuanced distinctions on the extent to which they did better with respect to their performance history (*"I didn't beat all my previous selves as three of them surpassed me but it was better than last time where four or five previous selves beat me."*, *"still can't beat the future speed but better than last time"*). This meant that even if they did not beat all their ghosts, they were able to at least acknowledge their improvement by beating some of their past performances – something that would not have been possible if they only competed against a single ghost.

By contrast, participants in NC tended to appraise their improvement by how much easier the task felt. Since there was no competition as a feedback mechanism, participants tended to rely on their fatigue levels as a barometer for performance improvement (*"I feel less tired"*, *"Sprints felt easier than previous sessions"*, *"feels easier every time"*) and hints of doubt were expressed at their progress (*"it was a little easier but I felt I made no progress"*). Some of the participants who reported the task was feeling easier actually did worse over time in terms of their power output, leading to inaccurate positive appraisals of their performance. In comparison, MG participants felt the satisfaction of not only the task feeling easier, but also doing better at the same time (*"especially in the first sprint, it felt much easier to beat my future and past self and it was really gratifying and felt much easier than previous times"*). Some participants attributed their performance improvement to both an increase in fitness and motivation (*"generally, I have been increasing in my performance session on session which shows that I am either getting fitter, being more motivated or a combination of the two. I think the likelihood is the latter, with an emphasis on the motivation aspect"*).

Theme 2: I work very hard to win

MG participants were determined to put their best effort forward to beat all of their ghosts. This was important in motivating participants to work harder than they otherwise normally would (*"I exerted myself more than last time and the past and future version of myself definitely motivated me to try harder"*, *"I tried harder to keep up with my best attempt and the future self so it was helpful having them there to push me"*, *"a great way to motivate myself to exercising more frequently and harder than I can independently push myself to"*). This determination to win suggests that the MG exergame was successful in capturing the competitive pressure that is characteristic of the racing experience. One participant even noted a sense of nervousness like the one felt before an important race (*"it felt a tiny bit stressful for some reason to come here, the same type of feeling as before a race or a competition"*). Indeed, the pressure to win had hints of anxiousness attached to it. For example, doing well in one session ratcheted up the pressure to do even better in the next (*"I managed to beat the computer-generated future versions of myself on both sprints... but this just means it'll be even harder for me to beat next time"*). Some feedback from MG participants suggests that the constant pressure for self-improvement might need to be punctuated by more relaxing sessions (*"competing against myself is something I might not do every day, just so that some sessions felt more relaxed, but pushed me a lot more to exert effort than my usual self-motivation"*).

NC participants in the longitudinal study who tried out MG for the first time in the cross-sectional study all noted how much more motivated they were to further exert themselves (*"[It went] really well, easily beat my future self in the first sprint and beat him again in the second. Best performance so far"*). Ghosts made it easier to gauge progress than mentally keeping track of metrics from past performances and were more salient in terms of improving motivation to exercise harder (*"being able to visualise your progress without having to write anything down is pretty awesome"*, *"really enjoyed the new aspect of the game. Helped with my competition as I am far better at competing against others (even though it is myself!) than pushing myself against numbers. I have been comparing myself against previous performances with a rough estimation in my head of average RPM within the sprints so really nice to get that within the game"*).

Theme 3: Outperforming my ghosts feels rewarding

MG participants felt a strong sense of satisfaction in beating their past and future ghosts and doing better overall. It was generally the sense of self-improvement that made beating ghosts feel very rewarding (*"satisfying knowing beat all past performances and was close to future"*, *"Today went very well, I managed to beat the computer-generated version of myself in both sprints and in the first sprint by a very large margin. I'm very happy with today's results"*, *"my past self coming up behind me or overtaking me really motivated me to go faster and I felt really good after beating them"*). Having more than one ghost to race against provided richer feedback on the player's progress, which helped to make the racing experience more enjoyable (*"The ghosts made the sprints much more interesting, and it was fun trying to beat my future self and seeing how well I did in the past")*.

The satisfaction of doing well was a key component of the MG exergame's enjoyment. While anybody participating in regular exercise is bound to feel some improvement over time, contextualising improvement by outperforming one's own performance history allowed participants to more viscerally enjoy their success along their fitness journey, which made the game very motivating (*"it was a really entertaining and encouraging way to do exercise. I usually struggle with motivating myself to exercise harder and tend to give up quite easily, but this game really motivated me to keep going and it gave me much more gratification than if I were exercising regularly without the game"*). Surpassing expectations was a sub-theme that contributed to the satisfaction of winning, which the MG exergame facilitated by allowing players to visualise the extent of their improvement (*"today went very well. I beat the first computer-generated future-self by even more than last time and I beat the second future-self as well but not quite as much as last time. I am very happy with my performance today* *though I can feel I am the most tired I have been so far in this study."*). The participants' satisfaction with beating their ghosts generally appeared to outweigh their exhaustion.

Theme 4: Losing to my ghosts feels frustrating

Because MG participants often worked very hard to win, losing felt particularly frustrating. The dynamics of the game was such that there was an implicit expectation to always do better after every session, so failing to live up to this may have been cause for disappointment (*"it's a lot less encouraging when I just had a better day recently and cannot beat that today"*, *"not good that my times are getting worse"*). It appears at the heart of this frustration was that, despite putting in a high amount of effort, participants were not always physically able to do better than their past performances. Before some sessions, participants were simply tired, e.g. from previous physical activity or lack of sleep, which had an impact on their performance (*"I felt quite tired today so I didn't do as well as I have in previous attempts. I found it hard to keep up with my past attempts and seeing them all quite a way in front of me was a little disheartening"*, *"my worse performance today may have been because I did two intense leg workouts yesterday, so my legs feel quite tired today"*). All MG participants experienced some sort of setback during the study but they seemed to acknowledge that this was part and parcel of the experience that could also motivate them to do better in future sessions (*"to be able to see myself improve is a small confidence boost. At the same time, I have a goal to reach (the future me) and I kind of understand that it's unrealistic for me to beat future me immediately"*, *"I felt really competitive against my future self today, especially after doing so badly last time."*).

DISCUSSION

Our goal was to create a rich self-competitive racing experience that motivates fitness improvement by having players race against their past and future selves (MG). While both MG and the non-competitive exergame (NC) led to performance improvements over four weeks of about 4.41W on average for each of the bi-weekly sessions, MG almost doubled ΔPower compared to NC (H1), increasing Power by about 16% compared to just 8% in NC. In contrast, studies on non-gamified HIIT using correlated measures of cardiovascular fitness such as peak power output and VO_2max [23, 22] typically report performance increase in the range of about 5-10% [62, 84, 144, 70, 21] and are often over markedly longer training periods than in our longitudinal study. Some HIIT studies show improvements in power output similar to those in MG, but these studies are either longer (6-8 weeks) [124, 99] or target specifically obese, inactive individuals where large initial improvements can be expected [83]. Such studies are hard to compare, so these numbers should be considered carefully; however, they are encouraging and indicate that MG compares favourably to other and even longer HIIT interventions. Exertion, Power, and HR are all highly correlated in exercise [6], so the large difference in Power between MG and NC supports that MG participants exerted themselves intensely relative to NC (H2) as well as in absolute terms [102]. Moreover, the thematic analysis highlighted that MG participants were very motivated to push themselves harder in each session in order to beat all their ghosts.

Despite exerting themselves more, participants found MG more intrinsically motivating than NC (H3) and had higher levels of perceived competence (H4) and flow, which are all positive predictors of long-term exercise adherence [2, 122, 51] (RQ2). There are indications that MG is particularly successful in eliciting intrinsic motivation based on enjoyment, satisfaction, and competence, as opposed to extrinsic motivation driven by external outcomes [121]. Overall, the longitudinal measurements compare favourably with those taken for a single gameplay session of other exergames [10, 72, 45, 125, 127]. In particular, MG led to significantly higher levels of intrinsic motivation and flow with similar performance compared to the single feedforward ghost used by Barathi et al. and Farrow et al. in a similar cycling exergame [10, 44]. This can be explained by the qualitative results, which highlight how players felt increasing satisfaction in beating more and more of their self-competitors, replicating aspects of a positive shared racing experience [146, 14, 134, 60]. Feedback also suggests that visualising progress through MG was able to cultivate a stronger sense of perceived competence because players were more cognisant of their improvements.

Participants always reported their satisfaction in the context of their improved performance, and this focus on self-improvement is more likely to be associated with intrinsic motivation [142, 53]. Participants whose sport-specific motivation focused on their own performance goals as opposed to beating others were more intrinsically motivated and achieved better performance outcomes. Indeed, participants in MG rated their effort highly and exerted themselves more intensely than in NC. Since higher-effort liked activities are more intrinsically motivating than lower-effort liked activities [143, 12], this could also help explain why exergaming under MG felt particularly satisfying. All this indicates that MG works well for people who are not competitive against others, i.e. those who have characteristics more typical of non-athletes [61], offering them some of the positive motivational and performance outcomes athletes derive from competitive racing.

The thematic analysis shows that the effects of MG on perceived competence were a double edged-sword: beating all the ghosts was very satisfying and made participants feel like they were making great progress – but losing against them sent a painfully clear message that they did worse. This is supported by the increased pressure and tension in MG compared to NC. The lack of such feedback in NC meant that participants did not experience the lows of losing against their ghosts nor the highs of beating them. Overall, participants found competing against themselves an encouraging way to do exercise and dealt well with the lows of losing against their ghosts. However, there is no denying that MG put constant pressure on participants to perform well, replicating some of the excitement, hope, stress, and anxiety competitive athletes experience when participating in a race [113, 7, 30, 68, 82].

The cross-sectional study results show that MG was superior to NC in terms of performance, intrinsic motivation, the absorption component of flow (but not balance), exercise self-efficacy, likely future usage, and overall preference (RQ3). Participants confirmed that competing against their past and future performances was their favourite aspect of the game and that it was the key motivating factor for investing a lot of effort in the exercise task. However, the longitudinal results suggest the idea that MG and NC could best be used in combination. Some participants found that occasionally playing the game under NC would be useful to punctuate the self-competitive pressure to always improve on one's performance, similar to the way athletes do not participate in a race every time they train. Finding a balance between different types of gameplay for longer-term exergaming is an interesting direction for future work. Because competitiveness is a personality trait [47] that affected the longer-term exergaming experience, the right balance will very likely depend on a player's personality.

Limitations

Our participants were mainly healthy individuals in their early 20s, which limits our ability to generalise the findings to other age groups and populations. Similarly, we only studied a single MG exergame, comparing it to only the same exergame without the self-competitive elements (NC). More research is needed to ascertain the effects of MG more widely, e.g. for non-VR exergames and non-HIIT exercise protocols. In this line, we did not investigate how MG compared to a similar exergame with only a single ghost. Because there are several ways of designing a self-model ghost, we would recommend this to be an area of future work as part of a broader research program spanning the design space of ghosts in exergames.

The logistics of organising a longitudinal study are always difficult and far surpass those required for cross-sectional studies. In our case, over 200 exergaming sessions were conducted in a limited amount of time. As a result, the sample size was not as high as desired. However, compared to many other longitudinal HIIT studies, our sample size was on the higher end of the spectrum [62, 84], and it was sufficient to draw clear statistical conclusions. Though we offer new insights into the longitudinal effects of high-intensity VR exergames, longer studies than our four week intervention need to be conducted to ascertain the longer term effects of MG on motivation, and to further mitigate any novelty effects. Inevitably, some exergaming sessions had to be re-arranged to fit around the busy schedules of our participants even if that meant that participants had less than a day's rest between sessions or that a calendar week would have three sessions instead of two. These cases were exceptions, affected both MG and NC in roughly equal measures, and did not coincide with any apparent outliers in the data. We believe their effect on the validity of the findings was negligible. In terms of aesthetics, the flashing emergency lights in the high-intensity phase may admittedly not be a good design choice for all players; they can be easily disabled without affecting the overall gameplay.

Impact and Implications for Exergaming Design

Motivating people to exercise at sufficient intensity is a well-known challenge [48, 104, 100, 18] that also exists in exergame design [109, 13, 10]. Based on our results, MG may be particularly suitable for making intense performance training more accessible to "average" people with busy lives; HIIT-based MG could be especially useful for achieving performance improvements quickly with a comparatively low volume of exercise. Our findings provide more evidence that self-competitive exergames can avoid the detrimental effects competing with others can have on intrinsic motivation. MG could be used to make competitive exergames more accessible and enjoyable to those demotivated by competition, including sedentary and obese individuals. It may help players to reap the benefits of a more demanding workout, gain self-efficacy, and perhaps even develop a taste for the thrill of competitive racing. Unlike previous cross-sectional studies, the longitudinal MG results suggest that self-competition could be a promising technique for promoting longer-term engagement with exercise and may help reduce the large dropout rates of many exercise programmes [4, 5, 36, 46].

Exergame designers could use MG to create personalised challenges that nudge players to continually improve at their own rate while promoting feelings of competence. The automatic setting and tracking of achievable performance targets via ghosts would be particularly useful for people who struggle with setting realistic exercise goals. Exergame designers could also use MG as an alternative to game balancing techniques that dynamically adjust the competition to be easier or harder based on the player's current performance. In exergames, such game balancing techniques can reduce feelings of relatedness and self-esteem [57] and can make winning less satisfying [3], whereas MG balances implicitly in the sense that a bad performance creates a ghost that can be overtaken more easily.

The promising effects of MG may make it an attractive method for not only gamifying HIIT, but other exercise protocols. The MG design concept could be fairly easily adapted to other types of racing exergames such as those based on running, rowing, or other ergometer-based gym equipment. There is even potential for applying MG to areas unrelated to exercise where the progression of an activity can be clearly visualised, e.g. more cognitive or skill-based tasks such as puzzle solving. This is an interesting direction for future work.

CONCLUSION

We investigated "multi-ghost" competition, a novel approach to self-competition by having players compete against multiple racing ghosts representing their past and projected future performances in a high-intensity cycling VR exergame. The empirical results from our longitudinal and cross-sectional studies suggest the following conclusions:

1. Multi-ghost competition can be an effective method for improving player performance over time.
2. Multi-ghost competition can improve predictors of exercise adherence such as intrinsic motivation, flow, and exercise self-efficacy.
3. Multi-ghost competition can convey some of the excitement of a typical competitive racing experience and is generally preferred over non-competitive gameplay.

Using multiple ghosts to enable self-competition between past, present, and future performances offers exciting possibilities for motivating rapid performance improvement in exergames and may also apply to other types of activities.

REFERENCES

[1] Terrence B Abney. 2007. The Importance of Perceived Competence in Fitness/Exercise Programming. *The Sport Journal* 5 (2007).

[2] Konstantinos Alexandris, Charalambos Tsorbatzoudis, and George Grouios. 2002. Perceived Constraints on Recreational Sport Participation: Investigating Their Relationship With Intrinsic Motivation, Extrinsic Motivation and Amotivation. *Journal of Leisure Research* 34, 3 (2002), 233.

[3] David Altimira, Florian Mueller, Gun Lee, Jenny Clarke, and Mark Billinghurst. 2014. Towards Understanding Balancing in Exertion Games. In *Proceedings of the 11th Conference on Advances in Computer Entertainment Technology*. ACM, 10.

[4] James Annesi. 2003. Effects of a Cognitive Behavioral Treatment Package on Exercise Attendance and Drop Out in Fitness Centers. *European Journal of Sport Science* 3, 2 (2003), 1–16.

[5] James J Annesi. 1998. Effects of Computer Feedback on Adherence to Exercise. *Perceptual and Motor Skills* 87, 2 (1998), 723–730.

[6] FJP Arts and H Kuipers. 1994. The Relation Between Power Output, Oxygen Uptake and Heart Rate in Male Athletes. *International Journal of Sports Medicine* 15, 05 (1994), 228–231.

[7] Michael Atkinson. 2008. Triathlon, Suffering and Exciting Significance. *Leisure Studies* 27, 2 (2008), 165–180.

[8] Kylie Ball, David Crawford, and Neville Owen. 2000. Obesity as a Barrier to Physical Activity. *Australian and New Zealand Journal of Public Health* 24, 3 (2000), 331–333.

[9] Albert Bandura. 2010. Self-Efficacy. *The Corsini Encyclopedia of Psychology* (2010), 1–3.

[10] Soumya C Barathi, Daniel J Finnegan, Matthew Farrow, Alexander Whaley, Pippa Heath, Jude Buckley, Peter W Dowrick, Burkhard C Wuensche, James LJ Bilzon, Eamonn O'Neill, and others. 2018. Interactive Feedforward for Improving Performance and Maintaining Intrinsic Motivation in VR Exergaming. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. ACM, 408–421.

[11] Gillian Barry, Brook Galna, and Lynn Rochester. 2014. The Role of Exergaming in Parkinson's Disease Rehabilitation: a Systematic Review of the Evidence. *Journal of NeuroEngineering and Rehabilitation* 11, 1 (2014), 33.

[12] Jonathan D Bartlett, Graeme L Close, Don PM MacLaren, Warren Gregson, Barry Drust, and James P Morton. 2011. High-Intensity Interval Running Is Perceived to Be More Enjoyable Than Moderate-Intensity Continuous Exercise: Implications for Exercise Adherence. *Journal of Sports Sciences* 29, 6 (2011), 547–553.

[13] Elaine Biddiss and Jennifer Irwin. 2010. Active Video Games to Promote Physical Activity in Children and Youth: A Systematic Review. *Archives of Pediatrics & Adolescent Medicine* 164, 7 (2010), 664–672.

[14] Stuart JH Biddle and Andrew B Hill. 1988. Causal Attributions and Emotional Reactions to Outcome in a Sporting Contest. *Personality and Individual Differences* 9, 2 (1988), 213–223.

[15] Paul Bliese. 2006. Multilevel Modeling in R (2.2)–A Brief Introduction to R, the multilevel package and the nlme package. (2006).

[16] John Bolton, Mike Lambert, Denis Lirette, and Ben Unsworth. 2014. PaperDude: A Virtual Reality Cycling Exergame. In *Proc. CHI Extended Abstracts*. ACM, 475–478.

[17] Gunnar Borg. 1998. *Borg's Perceived Exertion and Pain Scales*. Human Kinetics.

[18] Kerri N Boutelle, Robert W Jeffery, and Simone A French. 2004. Predictors of Vigorous Exercise Adoption and Maintenance Over Four Years in a Community Sample. *International Journal of Behavioral Nutrition and Physical Activity* 1, 1 (2004), 13.

[19] Virginia Braun and Victoria Clarke. 2006. Using Thematic Analysis in Psychology. *Qualitative Research in Psychology* 3, 2 (2006), 77–101.

[20] Tom Buggey and Lindsey Ogle. 2012. Video Self-Modeling. *Psychology in the Schools* 49, 1 (2012), 52–70.

[21] Kirsten A Burgomaster, George JF Heigenhauser, and Martin J Gibala. 2006. Effect of Short-Term Sprint Interval Training on Human Skeletal Muscle Carbohydrate Metabolism During Exercise and Time-Trial Performance. *Journal of Applied Physiology* 100, 6 (2006), 2041–2047.

[22] NK Butts, BA Henry, and D McLean. 1991. Correlations Between VO2max and Performance Times of Recreational Triathletes. *The Journal of Sports Medicine and Physical Fitness* 31, 3 (1991), 339–344.

[23] Daniel G Carey and Mark T Richardson. 2003. Can Aerobic and Anaerobic Power Be Measured in a 60-Second Maximal Test? *Journal of Sports Science & Medicine* 2, 4 (2003), 151.

[24] Rachel B Clancy, Matthew P Herring, and Mark J Campbell. 2017. Motivation Measures in Sport: A Critical Review and Bibliometric Analysis. *Frontiers in Psychology* 8 (2017).

[25] Avital Cnaan, Nan M Laird, and Peter Slasor. 1997. Using the General Linear Mixed Model to Analyse Unbalanced Repeated Measures and Longitudinal Data. *Statistics in Medicine* 16, 20 (1997), 2349–2380.

[26] Giant Bomb contributors. 2019. Ghost Racer (Concept). Wiki. (2019). Retrieved September 15, 2019 from https://www.giantbomb.com/ghost-racer/3015-3097/.

[27] Angela Cream, Sue O'Brian, Mark Onslow, Ann Packman, and Ross Menzies. 2009. Self-Modelling as a Relapse Intervention Following Speech-Restructuring Treatment for Stuttering. *International Journal of Language & Communication Disorders* 44, 5 (2009), 587–599.

[28] Mihaly Csikszentmihalyi. 1997a. Creativity: Flow and the Psychology of Discovery and Invention. *HarperPerennial, New York* 39 (1997).

[29] Mihaly Csikszentmihalyi. 1997b. *Finding Flow: The Psychology of Engagement with Everyday Life*. Basic Books.

[30] Lewis A Curry, CR Snyder, David L Cook, Brent C Ruby, and Michael Rehm. 1997. Role of Hope in Academic and Sport Achievement. *Journal of Personality and Social Psychology* 73, 6 (1997), 1257.

[31] Goodarz Danaei, Eric L Ding, Dariush Mozaffarian, Ben Taylor, Jürgen Rehm, Christopher JL Murray, and Majid Ezzati. 2009. The Preventable Causes of Death in the United States: Comparative Risk Assessment of Dietary, Lifestyle, and Metabolic Risk Factors. *PLOS Medicine* 6, 4 (2009), e1000058.

[32] Edward L Deci, Gregory Betley, James Kahle, Linda Abrams, and Joseph Porac. 1981. When Trying to Win: Competition and Intrinsic Motivation. *Personality and Social Psychology Bulletin* 7, 1 (1981), 79–83.

[33] Edward L Deci and Bradley C Olson. 2012. Motivation and Competition: Their Role in Sports. In *Sports, Games, and Play*. Psychology Press, 93–120.

[34] Edward L Deci and Richard M Ryan. 2010. Intrinsic Motivation. *The Corsini Encyclopedia of Psychology* (2010), 1–2.

[35] Raymond Desharnais, Jacques Bouillon, and Gaston Godin. 1986. Self-Efficacy and Outcome Expectations as Determinants of Exercise Adherence. *Psychological Reports* 59, 3 (1986), 1155–1159. DOI: http://dx.doi.org/10.2466/pr0.1986.59.3.1155

[36] Rod K Dishman. 1988. *Exercise Adherence: Its Impact on Public Health*. Human Kinetics.

[37] Rod K Dishman. 1991. Increasing and Maintaining Exercise and Physical Activity. *Behavior Therapy* 22, 3 (1991), 345–378.

[38] Christian Dormann, Doris Fay, Dieter Zapf, and Michael Frese. 2006. A State-Trait Analysis of Job Satisfaction: On the Effect of Core Self-Evaluations. *Applied Psychology* 55, 1 (2006), 27–51.

[39] Peter W Dowrick. 1999. A Review of Self Modeling and Related Interventions. *Applied and Preventive Psychology* 8, 1 (1999), 23–39.

[40] Peter W Dowrick. 2012a. Self Model Theory: Learning From the Future. *Wiley Interdisciplinary Reviews: Cognitive Science* 3, 2 (2012), 215–230.

[41] Peter W Dowrick. 2012b. Self Modeling: Expanding the Theories of Learning. *Psychology in the Schools* 49, 1 (2012), 30–41.

[42] Jon Dunaj. 2014. Investigating Flow, Presence, and Engagement in Independent Video Game Mechanics. (2014).

[43] Endomondo LLC. 2019. Endomondo. Mobile application software. (2019). Retrieved September 15, 2019 from https://apps.apple.com/us/app/endomondo/id333210180.

[44] Matthew Farrow, Christof Lutteroth, Peter C Rouse, and James LJ Bilzon. 2018. Virtual-Reality Exergaming Improves Performance During High-Intensity Interval Training. *European Journal of Sport Science* (2018), 1–9.

[45] Samantha Finkelstein, Andrea Nickel, Zachary Lipps, Tiffany Barnes, Zachary Wartell, and Evan A Suma. 2011. Astrojumper: Motivating Exercise With an Immersive Virtual Reality Exergame. *Presence: Teleoperators and Virtual Environments* 20, 1 (2011), 78–92.

[46] Canadian Fitness and Lifestyle Research Institute. 2005. 2005 Physical Activity Monitor. (2005).

[47] Thomas D Fletcher and David N Nusbaum. 2008. Trait Competitiveness as a Composite Variable: Linkages With Facets of the Big-Five. *Personality and Individual Differences* 45, 4 (2008), 312–317.

[48] Centers for Disease Control and Prevention. 2008. US Department of Health and Human Services Physical Activity Guidelines for Americans 2008. (2008).

[49] Kenneth R Fox and Magnus Lindwall. 2014. Self-Esteem and Self-Perceptions in Sport and Exercise. In *Routledge Companion to Sport and Exercise Psychology*. Routledge, 58–72.

[50] Lawrence D Frank, Martin A Andresen, and Thomas L Schmid. 2004. Obesity Relationships With Community Design, Physical Activity, and Time Spent in Cars. *American Journal of Preventive Medicine* 27, 2 (2004), 87–96.

[51] Christina M Frederick and Richard M Ryan. 1993. Differences in Motivation for Sport and Exercise and Their Relations With Participation and Mental Health. *Journal of Sport Behavior* 16, 3 (1993), 124.

[52] Christina M Frederick-Recascino, Hana Schuster-Smith, and others. 2003. Competition and Intrinsic Motivation in Physical Activity: A Comparison of Two Groups. *Journal of Sport Behaviour* 26, 3 (2003), 240–254.

[53] Márta Fülöp. 2009. Happy and Unhappy Competitors: What Makes the Difference? *Psihologijske Teme* 18, 2 (2009), 345–367.

[54] James Gadzik. 2006. "How Much Should I Weigh?" Quetelet's Equation, Upper Weight Limits, and BMI Prime. *Connecticut Medicine* 70, 2 (2006), 81–88.

[55] Zan Gao and S Chen. 2014. Are Field-Based Exergames Useful in Preventing Childhood Obesity? A Systematic Review. *Obesity Reviews* 15, 8 (2014), 676–691.

[56] Anne W Garcia and Abby C King. 1991. Predicting Long-Term Adherence to Aerobic Exercise: A Comparison of Two Models. *Journal of Sport and Exercise Psychology* 13, 4 (1991), 394–410.

[57] Kathrin Maria Gerling, Matthew Miller, Regan L Mandryk, Max Valentin Birk, and Jan David Smeddinck. 2014. Effects of Balancing for Physical Abilities on Player Performance, Experience and Self-Esteem in Exergames. In *Proceedings of the 32nd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 2201–2210.

[58] Martin J. Gibala. 2007. High-Intensity Interval Training: A Time-Efficient Strategy for Health Promotion? *Current Sports Medicine Reports* 6, 4 (01 Aug 2007), 211–213. DOI: http://dx.doi.org/10.1007/s11932-007-0033-8

[59] Martin J Gibala, Jonathan P Little, Maureen J MacDonald, and John A Hawley. 2012. Physiological Adaptations to Low-Volume, High-Intensity Interval Training in Health and Disease. *Journal of Physiology* 590, 5 (2012), 1077–1084.

[60] Alan St Clair Gibson, Jos J De Koning, Kevin G Thompson, William O Roberts, Dominic Micklewright, John Raglin, and Carl Foster. 2013. Crawling to the Finish Line: Why Do Endurance Runners Collapse? *Sports Medicine* 43, 6 (2013), 413–424.

[61] Diane L Gill and Thomas E Deeter. 1988. Development of the Sport Orientation Questionnaire. *Research Quarterly for Exercise and Sport* 59, 3 (1988), 191–202.

[62] Nicholas H Gist, Michael V Fedewa, Rod K Dishman, and Kirk J Cureton. 2014. Sprint Interval Training Effects on Aerobic Capacity: A Systematic Review and Meta-Analysis. *Sports Medicine* 44, 2 (2014), 269–279.

[63] Stefan Göbel, Sandro Hardy, Viktor Wendel, Florian Mehm, and Ralf Steinmetz. 2010. Serious Games for Health: Personalized Exergames. In *Proceedings of the 18th ACM International Conference on Multimedia*. ACM, 1663–1666.

[64] Laurie Grubbs and Jason Carter. 2002. The Relationship of Perceived Benefits and Barriers to Reported Exercise Behaviors in College Undergraduates. *Family & Community Health* 25, 2 (2002), 76–84.

[65] Maria Hagströmer, Pekka Oja, and Michael Sjöström. 2006. The International Physical Activity Questionnaire (IPAQ): A Study of Concurrent and Construct Validity. *Public Health Nutrition* 9, 6 (2006), 755–762.

[66] Pedro C Hallal, Lars Bo Andersen, Fiona C Bull, Regina Guthold, William Haskell, Ulf Ekelund, Lancet Physical Activity Series Working Group, and others. 2012. Global Physical Activity Levels: Surveillance Progress, Pitfalls, and Prospects. *The Lancet* 380, 9838 (2012), 247–257.

[67] Joshua C Haller, Young H Jang, Jack Haller, Lindsay Shaw, and Burkhard C Wünsche. 2019. HIIT The Road: Using Virtual Spectator Feedback in HIIT-based Exergaming. In *Proceedings of the Australasian Computer Science Week Multiconference*. ACM, 47.

[68] Yuri L Hanin. 2007. Emotions in Sport: Current Issues and Perspectives. *Handbook of Sport Psychology* 3, 3158 (2007), 22–41.

[69] Joel M Hektner and Mihaly Csikszentmihalyi. 1996. A Longitudinal Exploration of Flow and Intrinsic Motivation in Adolescents. (1996).

[70] Peter Herbert, LD Hayes, NF Sculthorpe, and Fergal M Grace. 2017. HIIT Produces Increases in Muscle Power and Free Testosterone in Male Masters Athletes. *Endocrine Connections* 6, 7 (2017), 430–436.

[71] Wijnand A IJsselsteijn, YAW De Kort, JHDM Westerink, M de Jager, and Ronald Bonants. 2006. Virtual Fitness: Stimulating Exercise Behavior Through Media Technology. *Presence: Teleoperators and Virtual Environments* 15, 6 (2006), 688–698.

[72] Christos Ioannou, Patrick Archard, Eamonn O'Neill, and Christof Lutteroth. 2019. Virtual Performance Augmentation in an Immersive Jump & Run Exergame. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, 158.

[73] Susan A Jackson and Mihaly Csikszentmihalyi. 1999. *Flow in Sports*. Human Kinetics.

[74] Asker E Jeukendrup and James Martin. 2001. Improving Cycling Performance. *Sports Medicine* 31, 7 (2001), 559–569.

[75] Michael A Kanters and Scott Forester. 1997. The Motivations and Self-Esteem of Intramural Sports Participants. *Recreational Sports Journal* 21, 3 (1997), 3–7.

[76] Tuomas Kari. 2014. Can Exergaming Promote Physical Fitness and Physical Activity?: A Systematic Review of Systematic Reviews. *International Journal of Gaming and Computer-Mediated Simulations (IJGCMS)* 6, 4 (2014), 59–77.

[77] Johannes Keller and Herbert Bless. 2008. Flow and Regulatory Compatibility: An Experimental Approach to the Flow Model of Intrinsic Motivation. *Personality and Social Psychology Bulletin* 34, 2 (2008), 196–209.

[78] Donald C Klein. 1991. The Humiliation Dynamic: An Overview. *Journal of Primary Prevention* 12, 2 (1991), 93–121.

[79] Leonie Klompstra, Tiny Jaarsma, and Anna Strömberg. 2013. An In-Depth, Longitudinal Examination of the Daily Physical Activity of a Patient With Heart Failure Using a Nintendo Wii at Home: A Case Report. *Journal of Rehabilitation Medicine* 45, 6 (2013), 599–602.

[80] Wolfgang Kramer. 2000. What Makes a Game Good. *Game & Puzzle Design, vol. 1, no. 2, 2015 (Colour)* (2000), 84.

[81] Carminda Maria Goersch Fontenele Lamboglia, Vanina Tereza Barbosa Lopes da Silva, José Eurico de Vasconcelos Filho, Mônica Helena Neves Pereira Pinheiro, Marilene Calderaro da Silva Munguba, Francisco Valmar Isaias Silva Júnior, Fernando Alberto Ramirez de Paula, and Carlos Antônio Bruno da Silva. 2013. Exergaming as a Strategic Tool in the Fight Against Childhood Obesity: A Systematic Review. *Journal of Obesity* 2013 (2013).

[82] Andrew M Lane, Mathew G Wilson, Gregory P Whyte, and Robert Shave. 2011. Physiological Correlates of Emotion-Regulation During Prolonged Cycling Performance. *Applied Psychophysiology and Biofeedback* 36, 3 (2011), 181–184.

[83] Stefano Lanzi, Franco Codecasa, Mauro Cornacchia, Sabrina Maestrini, Paolo Capodaglio, Amelia Brunani, Paolo Fanari, Alberto Salvadori, and Davide Malatesta. 2015. Short-Term HIIT and Fatmax Training Increase Aerobic and Metabolic Fitness in Men With Class II and III Obesity. *Obesity* 23, 10 (2015), 1987–1994.

[84] Paul B Laursen and David G Jenkins. 2002. The Scientific Basis for High-Intensity Interval Training. *Sports Medicine* 32, 1 (2002), 53–73.

[85] Seungmin Lee, Wonkyung Kim, Taiwoo Park, and Wei Peng. 2017. The Psychological Effects of Playing Exergames: A Systematic Review. *Cyberpsychology, Behavior, and Social Networking* 20, 9 (2017), 513–532.

[86] Alan D Lopez, Colin D Mathers, Majid Ezzati, Dean T Jamison, and Christopher JL Murray. 2006. Global and Regional Burden of Disease and Risk Factors, 2001: Systematic Analysis of Population Health Data. *The Lancet* 367, 9524 (2006), 1747–1757.

[87] Angela Lumpkin. 1983. Sport and Human Values. (1983).

[88] Andrew Macvean and Judy Robertson. 2013. Understanding Exergame Users' Physical Activity, Motivation and Behavior Over Time. In *Proc. CHI*. ACM, 1251–1260.

[89] Tímea Magyaródi, Henriett Nagy, Péter Soltész, Tamás Mózes, and Attila Oláh. 2013. Psychometric Properties of a Newly Established Flow State Questionnaire. *The Journal of Happiness & Well-Being* 1, 2 (2013), 85–96.

[90] Bess H Marcus, Vanessa C Selby, Raymond S Niaura, and Joseph S Rossi. 1992. Self-Efficacy and the Stages of Exercise Behavior Change. *Research Quarterly for Exercise and Sport* 63, 1 (1992), 60–66.

[91] Edward McAuley, Terry Duncan, and Vance V Tammen. 1989. Psychometric Properties of the Intrinsic Motivation Inventory in a Competitive Sport Setting: A Confirmatory Factor Analysis. *Research Quarterly for Exercise and Sport* 60, 1 (1989), 48–58.

[92] Edward McAuley, Dan Russell, and John B Gross. 1983. Affective Consequences of Winning and Losing: An Attributional Analysis. *Journal of Sport and Exercise Psychology* 5, 3 (1983), 278–287.

[93] Mike McNamee. 2002. Hubris, Humility, and Humiliation: Vice and Virtue in Sporting Communities. *Journal of the Philosophy of Sport* 29, 1 (2002), 38–53.

[94] Daniel R Mestre, Christophe Maïano, Virginie Dagonneau, and Charles-Symphorien Mercier. 2011. Does Virtual Reality Enhance Exercise Performance, Enjoyment, and Dissociation? An Exploratory Study on a Stationary Bike Apparatus. *Presence: Teleoperators and Virtual Environments* 20, 1 (2011), 1–14.

[95] Florian Mueller, Frank Vetere, Martin Gibbs, Darren Edge, Stefan Agamanolis, Jennifer Sheridan, and Jeffrey Heer. 2012. Balancing Exertion Experiences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 1853–1862.

[96] Justin Munafo, Meg Diedrick, and Thomas A Stoffregen. 2017. The Virtual Reality Head-Mounted Display Oculus Rift Induces Motion Sickness and Is Sexist in Its Effects. *Experimental Brain Research* 235, 3 (2017), 889–901.

[97] Jeanne Nakamura and Mihaly Csikszentmihalyi. 2014. The Concept of Flow. In *Flow and the Foundations of Positive Psychology*. Springer, 239–263.

[98] David L Neumann, Robyn L Moffitt, Patrick R Thomas, Kylie Loveday, David P Watling, Chantal L Lombard, Simona Antonova, and Michael A Tremeer. 2018. A Systematic Review of the Application of Interactive Virtual Reality to Sport. *Virtual Reality* 22, 3 (2018), 183–198.

[99] Niamh J Ní Chéilleachair, Andrew J Harrison, and Giles D Warrington. 2017. HIIT Enhances Endurance Performance and Aerobic Characteristics More Than High-Volume Training in Trained Rowers. *Journal of Sports Sciences* 35, 11 (2017), 1052–1058.

[100] US Department of Health and Human Services. 2013. *Healthy People 2010: Final Review*.

[101] US Department of Health, Human Services, and others. 2018. 2018 Physical Activity Guidelines Advisory Committee Scientific Report. (2018).

[102] American College of Sports Medicine. 2017. *ACSM's Guidelines for Exercise Testing and Prescription*. Lippincott Williams & Wilkins.

[103] Yoonsin Oh and Stephen Yang. 2010. Defining Exergames & Exergaming. *Proceedings of Meaningful Play* (2010), 1–17.

[104] Bruno RR Oliveira, Fabian A Slama, Andrea C Deslandes, Elen S Furtado, and Tony M Santos. 2013. Continuous and High-Intensity Interval Training: Which Promotes Higher Pleasure? *PLOS One* 8, 11 (2013).

[105] Jamie O'Neill. 2014. Super Mario Kart Review. Game review. (29 March 2014). Retrieved September 15, 2019 from `http://www.nintendolife.com/reviews/wiiu-eshop/super_mario_kart_snes`.

[106] Dennis W Organ and Charles N Greene. 1974. Role Ambiguity, Locus of Control, and Work Satisfaction. *Journal of Applied Psychology* 59, 1 (1974), 101.

[107] World Health Organization and others. 2014. *Global Status Report on Noncommunicable Diseases 2014*. Technical Report. World Health Organization.

[108] Frank J Penedo and Jason R Dahn. 2005. Exercise and Well-Being: A Review of Mental and Physical Health Benefits Associated With Physical Activity. *Current Opinion in Psychiatry* 18, 2 (2005), 189–193.

[109] Wei Peng, Jih-Hsuan Lin, and Julia Crouse. 2011. Is Playing Exergames Really Exercising? A Meta-Analysis of Energy Expenditure in Active Video Games. *Cyberpsychology, Behavior, and Social Networking* 14, 11 (2011), 681–688.

[110] R Lingyak Petosa and Brian Holtz. 2013. Flow for Exercise Adherence: Testing an Intrinsic Model of Health Behavior. *American Journal of Health Education* 44, 5 (2013), 273–277.

[111] James L Peugh. 2010. A Practical Guide to Multilevel Modeling. *Journal of School Psychology* 48, 1 (2010), 85–112.

[112] Rebecca M Puhl and Chelsea A Heuer. 2009. The Stigma of Obesity: A Review and Update. *Obesity* 17, 5 (2009), 941–964.

[113] John S Raglin. 2007. The Psychology of the Marathoner. *Sports Medicine* 37, 4-5 (2007), 404–407.

[114] Joyce S Ramos, Lance C Dalleck, Arnt Erik Tjonna, Kassia S Beetham, and Jeff S Coombes. 2015. The Impact of High-Intensity Interval Training Versus Moderate-Intensity Continuous Training on Vascular Function: A Systematic Review and Meta-Analysis. *Sports Medicine* 45, 5 (2015), 679–692.

[115] Johnmarshall Reeve and Edward L Deci. 1996. Elements of the Competitive Situation That Affect Intrinsic Motivation. *Personality and Social Psychology Bulletin* 22, 1 (1996), 24–33.

[116] Giuseppe Riva, Fabrizia Mantovani, Claret Samantha Capideville, Alessandra Preziosa, Francesca Morganti, Daniela Villani, Andrea Gaggioli, Cristina Botella, and Mariano Alcañiz. 2007. Affective Interactions Using Virtual Reality: The Link Between Presence and Emotions. *CyberPsychology & Behavior* 10, 1 (2007), 45–56.

[117] Cathy Robson, Neville Blampied, and Lawrence Walker. 2015. Effects of Feedforward Video Self-Modelling on Reading Fluency and Comprehension. *Behaviour Change* 32, 1 (2015), 46–58.

[118] James E Rohrer, J Rush Pierce Jr, and Claudia Blackburn. 2005. Lifestyle and Mental Health. *Preventive Medicine* 40, 4 (2005), 438–443.

[119] Julian B Rotter. 1966. Generalized Expectancies for Internal Versus External Control of Reinforcement. *Psychological Monographs: General and Applied* 80, 1 (1966), 1.

[120] Richard M Ryan. 1982. Control and Information in the Intrapersonal Sphere: An Extension of Cognitive Evaluation Theory. *Journal of Personality and Social Psychology* 43, 3 (1982), 450–461.

[121] Richard M Ryan and Edward L Deci. 2000. Intrinsic and Extrinsic Motivations: Classic Definitions and New Directions. *Contemporary Educational Psychology* 25, 1 (2000), 54–67.

[122] Richard M Ryan, Christina M Frederick, Deborah Lepes, Noel Rubio, and Kennon M Sheldon. 1997. Intrinsic Motivation and Exercise Adherence. *International Journal of Sport Psychology* 28, 4 (1997), 335–354.

[123] James F Sallis, Melbourne F Hovell, and C Richard Hofstetter. 1992. Predictors of Adoption and Maintenance of Vigorous Physical Activity in Men and Women. *Preventive Medicine* 21, 2 (1992), 237–251.

[124] Nicholas F Sculthorpe, Peter Herbert, and Fergal Grace. 2017. One Session of High-Intensity Interval Training (HIIT) Every 5 Days, Improves Muscle Power but Not Static Balance in Lifelong Sedentary Ageing Men: A Randomized Controlled Trial. *Medicine* 96, 6 (2017).

[125] Lindsay A Shaw, Jude Buckley, Paul M Corballis, Christof Lutteroth, and Burkhard C Wünsche. 2016a. Competition and Cooperation With Virtual Players in an Exergame. *PeerJ Computer Science* 2 (2016).

[126] Lindsay Alexander Shaw, Romain Tourrel, Burkhard Claus Wunsche, Christof Lutteroth, Stefan Marks, and Jude Buckley. 2016b. Design of a Virtual Trainer for Exergaming. In *Proceedings of the Australasian Computer Science Week Multiconference*. ACM, 63.

[127] Lindsay A Shaw, Burkhard C Wünsche, Christof Lutteroth, Stefan Marks, Jude Buckley, and Paul Corballis. 2015. Development and Evaluation of an Exercycle Game Using Immersive Technologies. In *Proc. Australasian Workshop on Health Informatics and Knowledge Management (HIKM)*. Australian Computer Society, 75–85.

[128] YunHee Shin, HeeJung Jang, and Nola J Pender. 2001. Psychometric Evaluation of the Exercise Self-Efficacy Scale Among Korean Adults With Chronic Diseases. *Research in Nursing & Health* 24, 1 (2001), 68–76.

[129] Nina Skjæret, Ather Nawaz, Tobias Morat, Daniel Schoene, Jorunn Lægdheim Helbostad, and Beatrix Vereijken. 2016. Exercise and Rehabilitation Delivered Through Exergames in Older Adults: An Integrative Review of Technologies, Safety and Efficacy. *International Journal of Medical Informatics* 85, 1 (2016), 1–16.

[130] Hayeon Song, Jihyun Kim, Kelly E Tenzek, and Kwan Min Lee. 2013. The Effects of Competition and Competitiveness Upon Intrinsic Motivation in Exergames. *Computers in Human Behavior* 29, 4 (2013), 1702–1708.

[131] Diane M Ste-Marie, Kelly Vertes, Amanda M Rymal, and Rose Martini. 2011. Feedforward Self-Modeling Enhances Skill Acquisition in Children Learning Trampoline Skills. *Frontiers in Psychology* 2 (2011), 155.

[132] Philip Stevens. 2017. NIKE's unlimited stadium in manila is the 'world's first LED running track'. News. (8 May 2017). Retrieved September 15, 2019 from `https://www.designboom.com/design/nike-unlimited-stadium-manila-worlds-first-led-running-track-05-08-2017/`.

[133] Tamara D Street, Sarah J Lacey, and Rebecca R Langdon. 2017. Gaming Your Way to Health: A Systematic Review of Exergaming Programs to Increase Health and Exercise Behaviors in Adults. *Games for Health Journal* 6, 3 (2017), 136–146.

[134] Jeffery J Summers, Victoria J Machin, and Gregory I Sargent. 1983. Psychosocial Factors Related to Marathon Running. *Journal of Sport and Exercise Psychology* 5, 3 (1983), 314–331.

[135] Jennifer Sween, Sherrie Flynt Wallington, Vanessa Sheppard, Teletia Taylor, Adana A Llanos, and Lucile Lauren Adams-Campbell. 2014. The Role of Exergaming in Improving Physical Activity: A Review. *Journal of Physical Activity and Health* 11, 4 (2014), 864–870.

[136] Marlene K Tappe, Joan L Duda, and Patricia M Ehrnwald. 1989. Perceived Barriers to Exercise Among Adolescents. *Journal of School Health* 59, 4 (1989), 153–155.

[137] Pedro J Teixeira, Eliana V Carraça, David Markland, Marlene N Silva, and Richard M Ryan. 2012. Exercise, Physical Activity, and Self-Determination Theory: A Systematic Review. *International Journal of Behavioral Nutrition and Physical Activity* 9, 1 (2012), 78.

[138] Brave the Skies. 2019. Ghostracer. Mobile application software. (2019). Retrieved September 15, 2019 from `https://play.google.com/store/apps/details?id=com.bravetheskies.ghostracer&hl=en`.

[139] Scott Thomas, Jeff Reading, and Roy J Shephard. 1992. Revision of the Physical Activity Readiness Questionnaire (PAR-Q). *Canadian Journal of Sport Sciences* (1992).

[140] Mark Stephen Tremblay, Rachel Christine Colley, Travis John Saunders, Genevieve Nissa Healy, and Neville Owen. 2010. Physiological and Health Implications of a Sedentary Lifestyle. *Applied Physiology, Nutrition, and Metabolism* 35, 6 (2010), 725–740.

[141] Robert J Vallerand, Lise I Gauvin, and Wayne R Halliwell. 1986. Negative Effects of Competition on Children's Intrinsic Motivation. *The Journal of Social Psychology* 126, 5 (1986), 649–656.

[142] Robert J Vallerand and Gaétan F Losier. 1999. An Integrative Analysis of Intrinsic and Extrinsic Motivation in Sport. *Journal of Applied Sport Psychology* 11, 1 (1999), 142–169.

[143] Alan S Waterman. 2005. When Effort Is Enjoyed: Two Studies of Intrinsic Motivation for Personally Salient Activities. *Motivation and Emotion* 29, 3 (2005), 165–188.

[144] Adele R Weston, Kathryn H Myburgh, Fiona H Lindsay, Steven C Dennis, Timothy D Noakes, and John A Hawley. 1996. Skeletal Muscle Buffering Capacity and Endurance Performance After High-Intensity Interval Training by Well-Trained Cyclists. *European Journal of Applied Physiology and Occupational Physiology* 75, 1 (1996), 7–13.

[145] Kassia S Weston, Ulrik Wisløff, and Jeff S Coombes. 2014. High-Intensity Interval Training in Patients With Lifestyle-Induced Cardiometabolic Disease: A Systematic Review and Meta-Analysis. *British Journal of Sports Medicine* 48, 16 (2014), 1227–1234. DOI: `http://dx.doi.org/10.1136/bjsports-2013-092576`

[146] George V Wilson and John H Kerr. 1999. Affective Responses to Success and Failure: A Study of Winning and Losing in Competitive Rugby. *Personality and Individual Differences* 27, 1 (1999), 85–99.

[147] José Pablo Zagal, Miguel Nussbaum, and Ricardo Rosas. 2000. A Model to Support the Design of Multiplayer Games. *Presence: Teleoperators & Virtual Environments* 9, 5 (2000), 448–462.

[148] Nan Zeng, Zachary Pope, Jung Lee, and Zan Gao. 2018. Virtual Reality Exercise for Anxiety and Depression: A Preliminary Review of Current Research in an Emerging Field. *Journal of Clinical Medicine* 7, 3 (2018), 42.

[149] Eleni Zetou, Thomas Kourtesis, Katerina Getsiou, Maria Michalopoulou, Efthimis Kioumourtzoglou, and others. 2008. The Effect of Self-Modeling on Skill Learning and Self-Efficacy of Novice Female Beach-Volleyball Players. *Athletic Insight: The Online Journal of Sport Psychology* 10, 3 (2008).